Electronic Transport in Underdoped YBCO Nanowires: Possible Observation of Stripe Domains

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We have measured the transport properties of a series of underdoped $YBa_2Cu_3O_{7-\delta}$ nanowires fabricated with widths of 100-250 nm. We observe large telegraph-like fluctuations in the resistance between the pseudogap temperature T^* and the superconducting transition temperature T_c, consistent with the formation and dynamics of a domain structure such as that created by charge stripes. We also find anomalous hysteretic steps in the current-voltage characteristics well below T_c.

Despite years of intense study of the high-T_c cuprates, many key questions remain unresolved, particularly regarding the microscopic details of the pairing mechanism, the nature of the pseudogap state, and the relationship between the superconducting and pseudogap states. One prominent category of high-T_c models involves the presence of a symmetry-breaking, non-superconducting order parameter that competes or coexists with superconductivity. Examples of such ordering are various orbital current models [1, 2, 3] and charge stripe ordering [4, 5, 6, 7]. A signature of underlying order would be the formation of domains separating various phases or orientations of the order parameter. To date, experimental evidence for such domains is suggestive but inconclusive. Neutron scattering data [8, 9, 10] and transport measurements [11] have been interpreted as support for charge ordering and stripe formation. STM spectroscopy imaging has revealed electronic phase separation into mesoscopic scale superconducting and pseudogap domains [12], and stripe features that have been attributed to charge stripes [13], quasiparticle interference fringes [14], and incommensurate spin-density waves [15].

In this Letter, we report transport measurements on nanoscale YBCO samples that show large amplitude switching noise in the resistance at temperatures above the superconducting transition temperature T_c but below the pseudogap temperature T^*, and hysteretic voltage steps in the current-voltage characteristics well below T_c. We argue that the resistance fluctuations may be a signature of the formation and dynamics of a symmetry-breaking domain structure arising from charge ordering into stripes. We consider whether the voltage steps could arise from a similar mechanism or are caused by heating or phase slips in the nanowire.

The key to the experiments is the fabrication of nanowires without significant degradation of their superconducting properties. We start with YBCO thin films (thickness 50-100 nm), grown by pulsed laser deposition on $LaAlO_3$ (LAO) substrates, with T_c's from $\sim$ 92 K (optimal doping) to $\sim$ 60 K on the underdoped side, as determined by a two-coil inductive measurement. We then dc sputter a carbon layer ($\sim$ 200 nm) and a thin gold layer ($\sim$ 20 nm) to serve as an etching template and to protect the film during processing. Patterning is done by electron beam lithography and ion beam etching on a liquid nitrogen cooled stage to avoid film degradation. Finally, the protective layers are removed and standard photolithography is used to attach leads to the nanowire.

Four-point resistance measurements on short ($\sim$ 500 nm) segments of the nanowires revealed surprising results. The overall shape of the resistance vs. temperature curves is as expected for underdoped films: as the temperature is lowered, the typical linear decrease in resistivity becomes sublinear below a temperature T^* normally associated with the pseudogap temperature, followed by the transition into the superconducting state. This is shown in Figure 1(a) for both a 3 μm line and a 250 nm wide nanowire. The transition width is typically 3-5 K with an onset at most a few degrees below the transition temperature of the starting uniform film. However,

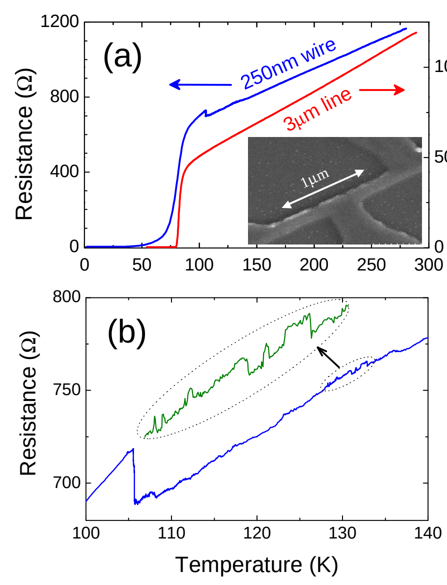

FIG. 1: (a) Resistance vs. temperature of a 500 nm segment of a 250nm wide nanowire compared to that of a 3 μm line. (b) Expanded section showing telegraph-like switching fluctuations at temperatures below approximately $150K$.

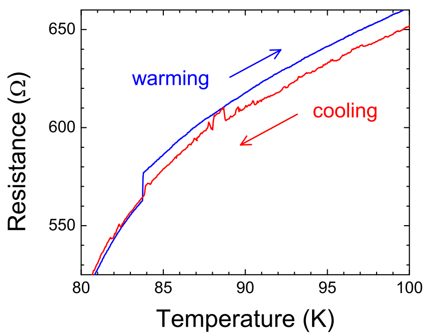

FIG. 2: Successive cooling and warming resistance vs. temperature for a 250 nm wide nanowire. Between 87-89 K, the cooling sweep exhibits multiple-level switching, with the high resistance state matching that established in the warming run.

between a temperature $\sim T^*$ and T_c, the nanowire exhibited large switching fluctuations of order 0.5-5% in the resistance, as expanded in Figure 1(b). The largest discrete resistance jump is nearly a 4% change, and is preceded by smaller ($\sim 1\%$) fluctuations. Also of interest are the change in slope of R(T) and the absence of large fluctuations immediately after the large 4% switch. Such switches are not seen in the wider line.

Data from another sample shown in Figure 2 demonstrates the behavior of the fluctuations upon successive cooling and warming data runs. Some features in the two runs are correlated, such as the jumps in the resistance at 84 K, while others appear only when heating or cooling. The switching fluctuations seen in the cooling curve appear to be telegraph-like two-state or multiple-level switching with the highest resistance state achieved corresponding to that measured during the the warming curve. Simultaneous measurements on adjacent segments suggest that most of the fluctuations are localized over regions ≤ 100 nm, but in a few cases correlations over extended length scales ≥ 1 μm were also observed.

We have observed such switching in more than five different nanowire samples. All of the samples studied are slightly underdoped with T_c's of 70-80 K. Thus, the pseudogap crossover temperature T^* should be roughly 50-100 K above T_c. This is indeed the case in those samples in which we can identify T^* as the temperature at which $R(T)$ deviates from a linear variation. We observe the large resistance fluctuations in approximately the same temperature range above T_c and never above 200 K. Thus, although T^* and the onset temperature of the switching noise are difficult to determine clearly in some nanowires, it is our impression that the large resistance fluctuations occur only in the temperature range between T_c and T^*, suggesting that they may be a feature of the pseudogap regime. We have not made a systematic study vs. sample width, but larger samples of width 3-5 μm do not display large resistance fluctuations.

If the temperature is held fixed and the resistance is monitored, it is sometimes possible to observe fluctuations in real time. An example is shown in Figure 3(a). The fluctuations with amplitude $\approx$ 0.25% have rather slow dynamics with switching times on the order of one second. The sample appears to prefer two states but, unlike a true two-level system, intermediate metastable states are also present. A histogram of the resistance states demonstrating a bimodal distribution is shown in Figure 3(b). Time traces taken at higher temperatures well above T^* did not exhibit bimodal switching.

Switching fluctuations in the resistance of conducting wires with the large magnitude and the extended spatial range that we observe are rare and difficult to explain. One possible mechanism is the motion of extended defects such as dislocations which could affect conduction channels. However, in this case it is difficult to explain why the large fluctuations are seen only in the temperature span $T_c < T < T^*$. Other explanations would seem to require the existence of a fluctuating domain structure with a conductivity asymmetry or anisotropy.

One mechanism that incorporates adequately all of the observed phenomena is the formation of charge stripes characterized by a local anisotropy in the conductance. Since the nanowires studied are aligned with the a or b crystalline axes, such stripes would naturally lead to a structure of domains aligned either parallel or perpendicular to the measuring current flow. The two orientations would have different critical currents, normal state resistances, and current-voltage characteristics, with parallel sections exhibiting a 1D wire behavior and perpendicular sections described by tunneling between charge stripes. If these domains were to move, reorient, and/or change size, as would be expected at higher temperatures, resistance fluctuations would result. If we assume a typical domain size given by the stripe correlation length $\Lambda \approx$ 35-40 nm [9], then the nanowire segments we have measured would contain roughly a 5 x 20 array of domains. Thus, a large resistivity change in one such domain would result in a nanowire resistance change of order 1%, in agreement with the observed values.

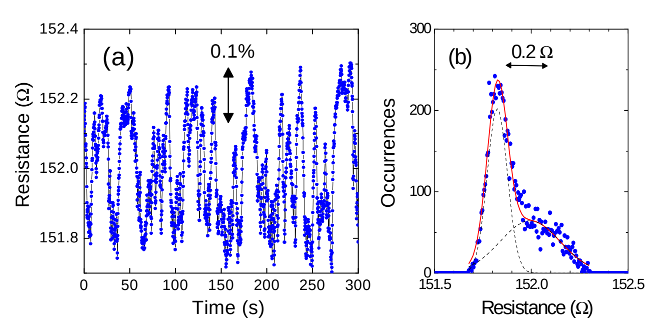

FIG. 3: (a) Resistance vs time at 100 K exhibits large 0.25%, telegraph-like fluctuations. (b) Histogram of resistance values demonstrating bimodal behavior.

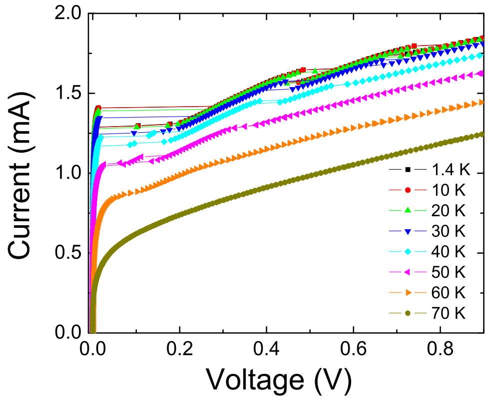

FIG. 4: Current-voltage characteristics of a nanowire at different temperatures showing a phase-diffusion regime at low voltage and multiple hysteretic steps at higher current levels.

The two most challenging aspects of the data to explain are the delocalized nature of the resistance changes and the slow switching kinetics observed. The stripe model provides a natural potential explanation for the extended spatial correlations since each Cu-O_2 plane of the layered YBCO structure may exhibit stripe alignment independent of the others. Alternatively, it has been suggested that cuprate nanowires may exhibit edge states that would show up as extended domains in the transport properties [16]. The edges may also affect the stripe dynamics by forcing a preferred stripe domain alignment and pinning domain wall motion, hence slowing the kinetics down to the timescales we observe. We find no evidence that the stripe domains are aligned by current flow since the current-voltage (IV) characteristics of the wire in the normal state are found to be strictly linear up to currents of 100 μA.

Intriguing features are found in the IV curves at low temperatures, as shown in Figure 4 for a nanowire segment of length 500 nm and width 200 nm measured at different temperatures. As the current is increased we find the onset of a finite phase diffusion voltage at a critical current I_c, followed by two or more hysteretic steps. The linear portions after each step have a large excess current and do not extrapolate to the origin, indicating that they are not simply localized ohmic sections in the wire but instead likely involve dynamical phase evolution. Simultaneous IV's on different but overlapping segments indicate that the first large step is always extended over several microns as in the normal state resistance measurements, but other steps may be either extended or localized in a single segment of the sample. Although this behavior could suggest more than one mechanism for dissipation in the wire, the different features may also arise from different vertical (c-axis) layers of the sample.

We have found it difficult to explain the voltage steps by standard mechanisms for the onset of resistance in superconducting wires. We have considered explanations based on weak links between grains, vortex flow, phase dynamics (phase slip centers), heating, and defect dynamics and find that they cannot readily account for the multiple voltage steps and their spatial correlations.

An obvious candidate for steps in the current-voltage characteristics is weak links at localized spots in the wire. The primary argument against these is that the low temperature critical current density measured in our wires is very high ($> 10^7$ A/cm^2), comparable to that of uniform thin films. Films grown by pulsed laser deposition have a high density of twin and low-angle grain boundaries, but these exhibit strong coupling rather than Josephson behavior, giving large J_c values of the order we observe [17]. An explanation of our IV results based on vortex entry and flux flow can also be ruled out. The flux flow resistivity in a magnetic field B scales as $\rho_f = \rho_n(B/H_{c2})$, where ρ_n is the normal state resistivity and H_{c2} is the upper critical field. For the cuprates H_{c2} is very large ($>$ 100 T), thus for the small fields generated by the currents in our nanowires, ρ_f will be too low by several orders of magnitude to produce the linear segments of the nanowire IV's observed between voltage steps. However, flux flow does likely account for the onset of voltage in the phase diffusion regime just above I_c.

Phase slip centers, the one-dimensional equivalent of dynamical vortex flow, only occur in samples with widths $\lesssim \xi$, the superconducting coherence length. For YBCO, $\xi \sim 2$ nm so our samples are substantially larger, with widths $\approx 50 - 100\ \xi$. Thus, phase slip centers are an unlikely explanation. However, a similar phenomena termed phase-slip lines may occur even in wider lines [18]. These may be thought of resulting from the flow of kinematic vortices [19], with properties intermediate between Abrikosov and Josephson vortices. These could be responsible for localized steps in the IV characteristics but cannot easily explain their extended nature.

A serious concern in measurements on current-carrying nanostructures is local heating, which can cause localized regions of the sample to exceed the critical temperature or critical current [20]. It is plausible that the steps in the current-voltage characteristics could arise from this mechanism. However, heating may not be as serious a problem in our cuprate samples as in other nanostructures. Because of the high T_c, a substantial local temperature rise is required to induce normal transitions at the lowest measurement temperatures. At the same time, cuprate films are extremely well thermally-anchored to the substrate because LAO has a reasonably good thermal conductivity [21] and the thermal boundary resistance between the sample and substrate is very low due to their structural similarity [22]. To estimate the local temperature rise from ohmic heating, we have modelled the heat flow from a nanowire into the substrate, assuming that the sample attains a steady-state temperature at each current-voltage point. For a nanowire of width w and length $L >> w$, the local temperature at the center

of the sample for uniform power dissipation $P = IV$ is approximately given by

$$T(P) \;=\; \left\{ T_{base}^2 + \frac{P}{\pi\alpha L}\; ln \left[\frac{(L^2+w^2)^{1/2}+L}{(L^2+w^2)^{1/2}-L} \right] \right\}^{1/2} \quad (1)$$

where T_{base} is the sample temperature with no current. This expression is valid in the temperature regime for which the thermal conductivity of the substrate has the linear form $\kappa = \alpha T$; in other regimes, the nanowire temperature must be computed numerically.

As an example, we consider the nanowire IV at $T_{base} =$ 1.4 K shown in Fig. 4, for which $L = 500$ nm and $w = 200$ nm. The thermal conductivity of LAO is linear in temperature for $T < 25$ K with $\alpha = 2.08$ W/m-K^2, peaks at $T \sim 30$ K, and then drops roughly as $T^{-1/2}$. We plot the calculated nanowire temperature as a function of the current I in Fig. 5. The nanowire temperature heats substantially at the highest currents, especially after the temperature becomes high enough that the thermal conductivity drops, but the temperature at the first observed voltage jump is predicted to be less than 5 K. Inhomogeneities in the current-flow and or conductance of the wire will enhance the local heating. We simulate these possibilities by considering a narrower wire with $w = 10$ nm, corresponding to a filamentary conduction path, and a shorter resistive section with $L = 100$ nm, corresponding to a localized resistive section. The temperature rise in these cases is larger but never exceeds 12 K at the first jump, well below the sample T_c. Thus, although the heating is substantial in our nanowires, it does not obviously explain the observed voltage steps. We note that the calculated temperature rise for the normal state resistance measurements is negligible at the power levels used ($\sim$ 0.1-10 μW).

It is conceivable that the step structure could also be a manifestation of the stripe domain structure suggested by the resistance data. If there are a series of domains aligned parallel and perpendicular to the current direction, different domains could switch into the normal state at different currents, leading to multiple steps in the nanowire current-voltage characteristics. Once a normal section is created, the heating described above could drive large sections of the nanowire into the normal state. A detailed model has not been developed for this scenario.

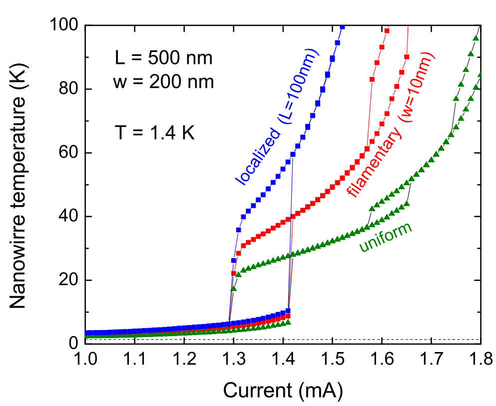

FIG. 5: Sample temperature as a function of current for the nanowire IV shown in Fig. 4 at $T = 1.4$ K, assuming uniform, filamentary, and localized dissipation.

In conclusion, we have fabricated and measured the transport properties of underdoped YBCO nanowires, giving a direct picture of what occurs on mesoscopic length scales. We observe discrete switching noise in the resistance of the nanowires in the range $T_c < T < T^*$. This may be a signature of the formation of a domain structure of charge stripes, which introduces a local conductance anisotropy and allows domain dynamics.

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